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16. ABSTRACT

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Long-Term Distributions of Annual Sediment Yields From Small Watersheds

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Annual sediment yields from small (<20 km²) mountain watersheds in the northwestern United States are approximately log normally distributed over time. Stochastic sediment yield models, based on brief, infrequent transport events, reproduce the log normal property. Observed cumulative distributions of annual yields from several Pacific Northwest drainages also appear to be log normal. The property gives a statistical basis for interpreting annual yield data. For example, impacts of watershed disturbance should be assessed by median rather than mean annual yield.

INTRODUCTION

Sediment production from small mountain watersheds is highly variable over time, even if land use patterns remain unchanged. Consequently, when a watershed is altered, as by timber harvest, it is difficult to attribute changes in sediment yields to harvesting alone. The variability is reduced if sediment yield observations are accumulated over an entire year. Often annual yields reflect neither seasonal runoff patterns nor the week-to-week variability due to random storm events. In addition, measurements of total annual yield constitute a conveniently small set of numbers which summarize the sediment production of a watershed.

Unfortunately, even annual totals are highly variable for many small basins. Until recently, sediment yield records were too brief to describe this variability. As a result, statistically valid, direct comparisons of sediment yields before and after land use changes have rarely been possible.

This paper suggests that annual sediment yields from small, relatively steep watersheds are approximately log normally distributed over time. Log normal distributions of synthetic annual yields are generated by simple stochastic models of runoff and sediment transport. In addition, several of the longest (5–20 years) annual yield records from small watersheds in the Pacific Northwest show the log normal property. If annual yields are in fact log normally distributed, then we begin to have a statistical basis for interpretation of data from short-term (1–5 years) sediment-monitoring programs.

A SIMPLE STOCHASTIC MODEL

A useful empirical model of sediment yield dynamics is obtained by viewing sediment transport as a sequence of discrete pulses or 'events.' The event sequence constitutes a partial duration series for discharge [*Todorovic*, 1978]. For a particular stream one constructs the series by extracting all segments of the continuous hydrograph which lie above some discharge threshold Q_T. Each period of high flow is an event, and the peak discharge and sediment yield are recorded for each event.

From these data one can parameterize a simple stochastic model of runoff and sediment yield. The number of events in any time interval $[0, t]$ is described by a time-dependent Poisson process [*Gupta et al.*, 1976; *Todorovic*, 1978]. In this paper we are interested primarily in annual totals, and the stochastic equations need not be presented. Instead, let N be the number of events which occur in 1 year. The N is assumed to be a Poisson-distributed random variable with parameter $\lambda = E[N]$. The probability mass function is given by

$$p_k = \text{Prob}\,[N = k] = e^{-\lambda}\,\frac{\lambda^k}{k!} \qquad k = 0, 1, 2, \cdots \tag{1}$$

To model discharge levels, let Q_j be discharge and $Q_j^* = (Q_j - Q_T)$ be the exceedance level for event j. The exceedances $\{Q_j^*\}$ are assumed to be a sequence of independent, identically distributed random variables with a common cumulative distribution function (cdf). Sediment yield Y_j for the jth event is related to discharge level by a power function:

$$Y_j = aQ_j^b \qquad \forall\, j \tag{2}$$

For a particular stream the constants a and b are estimated from the log transformed (Q, Y) observations by means of simple linear regression. Equation (2) is commonly called a sediment rating curve. As a result of (2), the sequence $\{Y_j\}$ is also a set of independent, identically distributed random variables, with common cdf, $F_Y(y) = P[Y_j \leq y]$, for all j.

Finally, the annual sediment yield Y_A is the sum of a random number of randomly large yields:

$$Y_A = \sum_{j=1}^{N} Y_j \tag{3}$$

The central claim of this paper is that the random variable Y_A is approximately log normally distributed for small, mountainous watersheds.

The preceding model is a distillation of several previous approaches. Sediment rating curves and flow duration curves are routinely combined to give estimates of mean annual sediment yield [*U.S. Department of Agriculture*, 1975]. *Gupta et al.* [1976] and *Todorovic* [1978] discuss event-based stochastic runoff processes, and *Woolhiser and Todorovic* [1974] couple runoff processes to several stochastic sediment models, including the one described here. *Renard and Lane* [1975] combine a stochastic runoff model with deterministic sediment transport equations in order to synthesize series of annual yields. *Woolhiser and Todorovic* [1974] and *Renard and Lane* [1975] apply the model only to ephemeral streams. In these systems, sediment transport events are obviously distinct. However, the model should apply almost as well to any small stream with continuous low flows which carry a small fraction of the total load.

SYNTHETIC ANNUAL YIELDS

The event-based model was applied to two watersheds, Flynn Creek (202 ha) and Needle Branch (75 ha), in the Ore-

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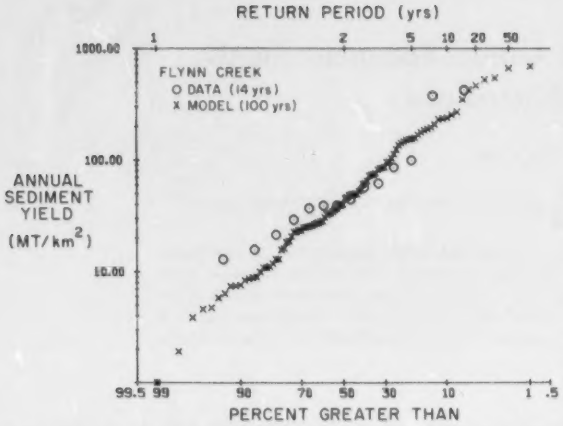

Fig. 1. Annual sediment yields (metric tons/km²) from Flynn Creek in the Pacific Northwest. Data are for conventional water years (October 1–September 30). Watershed characteristics are listed in Table 1.

gon coast range. The watersheds were forested with Douglas fir and alder and have mean slopes of 35 and 50%, respectively. Daily suspended sediment yield and mean discharge were recorded for 14 water years as part of the Alsea Watershed study [*Harris*, 1977; *Beschta*, 1978]. Midway through the period of record, Needle Branch was 82% clear-cut, following logging road construction. Flynn Creek remained undisturbed throughout the study. The hydrologic and sediment yield characteristics of these watersheds have already been extensively analyzed [*Brown and Krygier*, 1971; *Harr et al.*, 1975; *Harris*, 1977; *Beschta*, 1978].

Model parameters were estimated for the 14-year Flynn Creek record and the 7-year, prelogging record from Needle Branch. Annual sediment yields in Needle Branch following logging showed a definite decrease over time as vegetation became reestablished on the watershed [*Beschta*, 1978]. This decreasing trend is frequently seen in forested watersheds as evidence that sediment yields in these systems are limited by available sediment supplies (M. Fogel, personal communication, 1980). Thus (2), which assumes a stationary discharge-sediment relationship, is a poor model for Needle Branch following logging.

The supply limitation of forested drainages can also cause a seasonal nonstationarity in sediment yields. As the rainy season progresses, available sediment is gradually flushed from the watershed and sediment yields per unit discharge are reduced. For Flynn Creek and Needle Branch, *Beschta* [1978] showed that monthly mean concentration–discharge regressions before and after the yearly peak flow were significantly different. However, I found no seasonal trends in the same data when (2) was applied to high-flow events [*Van Sickle*, 1981]. As a result, I chose to apply the stationary model (2) to the event series. Since the seasonal trends, if they do exist, are periodic, the use of average, constant parameters may reduce the coefficient of determination in the regression (2), but the model's predictions should not be significantly biased.

An event was defined to be a continuous sequence of days during which mean daily discharge Q exceeded the flow threshold Q_T. For event j the representative discharge Q_j was the peak mean daily value during the event. The sediment yield Y_j was calculated from the data by summing the daily yields over the duration of the event. The discharge-sediment pairs (Q_j, Y_j), $j = 1, 2, \cdots$ were used to estimate model parameters. In both applications a flow threshold of $Q_T = 0.16$ m³ km^{-2} s^{-1} was used. The days during which Q was greater than Q_T constituted about 11% of the total period and accounted for more than 93% of the suspended sediment in both cases. A gamma distribution described the flow exceedances $\{Q_j^*\}$. Parameter estimates and further details of model fitting can be found in the work by *Van Sickle* [1981].

Figures 1 and 2 compare synthetic sequences of annual yields to observed values for the two streams. The plots indicate that the model reasonably predicts long-term annual yield distributions, and this feature is fully discussed by *Van Sickle* [1980]. Here we are primarily interested in the fact that both synthetic and observed annual yields appear quite linear on logarithmic, normal probability plots. That is, annual yields appear log normally distributed.

Renard and Lane [1975] produce similar results with a different stochastic model. In their Monte Carlo study, runoff events occurred according to a Poisson process, with log normally distributed runoff volumes. The start of the runoff season and the time of day at which each event began were also random variables. However, Renard and Lane used a mechanistic discharge-sediment relationship. Their model was applied to two ephemeral streams in southeastern Arizona. Fifty-year synthetic sequences of total annual sediment load were generated and plotted on log probability paper. The plots are linear. Renard and Lane fitted log normal distributions to the synthetic values and used the distributions to estimate annual yields for various return periods.

Observed Annual Yields

Forest land managers in the Pacific Northwest have become increasingly concerned with the effects of logging operations on the water quality of headwater streams. As a result, sediment-monitoring programs have been conducted on several small watersheds for more than 5 years.

A catalog of Pacific Northwest sediment data has been compiled for the U.S. Forest Service [*Larson and Sidle*, 1980]. From this catalog, records of annual suspended sediment yields were selected for watersheds ranging in size from about 0.1 to 20 km². Only continuous record segments greater than 5 years in length were chosen, with the further restriction that no significant land use change, such as timber harvest, oc-

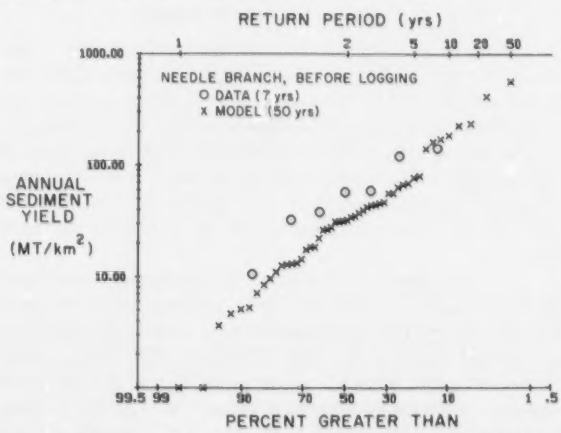

Fig. 2. The same as in Figure 1 but from Needle Branch, before logging.

TABLE 1. Watershed Characteristics for Figures 1–5

Watershed	Location	Area, km^2	Mean Slope, %	Annual Precipitation, cm	Years of Record	Data Type*	$\hat{\sigma}_z$†	χ^2 Test of Log Normality (p value, d.f.)	Reference
Flynn Creek (observed)	Oregon coast range	2.02	35	250	14	SS	1.0	0.59, 1	*Beschta* [1978] and *Van Sickle* [1981]
Flynn Creek (synthetic)	Oregon coast range	2.02	35	250	100	SS	1.4	0.69, 11	*Beschta* [1980] and *Van Sickle* [1981]
Needle Branch prelog (observed)	Oregon coast range	0.75	50	250	7	SS	0.9	‡	*Beschta* [1980] and *Van Sickle* [1981]
Needle Branch prelog (synthetic)	Oregon coast range	0.75	50	250	50	SS	1.4	0.24, 7	*Beschta* [1980] and *Van Sickle* [1981]
WS1	Oregon Cascades	0.96	63	230	10	SS + DB	0.8	0.52, 1	*Fredriksen* [1970] and R. L. Fredriksen (unpublished data, 1980)
WS2	Oregon Cascades	0.60	61	230	20	SS + DB	1.1	0.52, 2	*Fredriksen* [1970] and R. L. Fredriksen (unpublished data, 1980)
WS3	Oregon Cascades	1.01	53	230	11	SS + DB	1.2	0.76, 1	*Fredriksen* [1970] and R. L. Fredriksen (unpublished data, 1980)
WS9	Oregon Cascades	0.09	>60	230	9	SS	1.3	‡	*Harr and McCorison* [1979] and R. L. Fredriksen (unpublished data, 1980)
WS10	Oregon Cascades	0.10	>60	230	6	SS	1.5	‡	*Harr and McCorison* [1979] and R. L. Fredriksen (unpublished data, 1980)
Caspar Creek, North fork	northern California	5.08	30	102	14	SS	1.2	0.59, 1	*Rice et al.* [1979]
Horse Creek, east fork	Idaho	14.50	36	114	14	DB	0.6	0.59, 1	*King* [1980]
Horse Creek, main fork	Idaho	16.80	31	114	14	DB	0.7	0.59, 1	*King* [1980]

*SS = suspended sediment; DB = sediment trapped in debris basin.
†Sample estimate of σ_z = standard deviation [$\log_e Y_A$].
‡Insufficient record length.

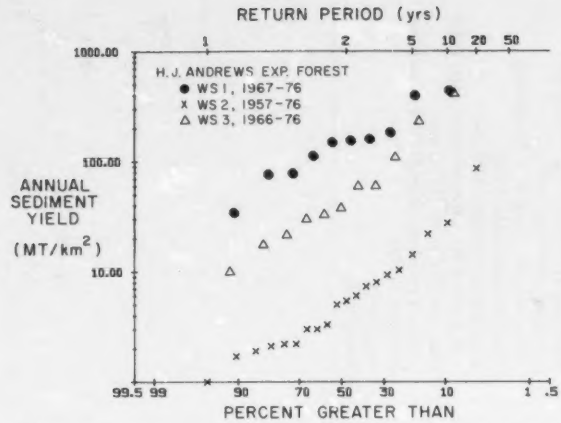

Fig. 3. The same as in Figure 1 but from sites in the H. J. Andrews Experimental Forest.

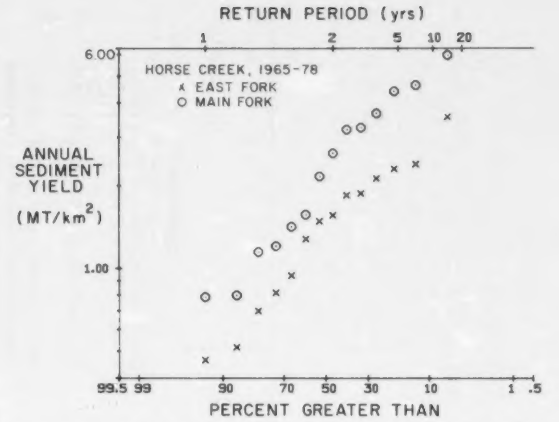

Fig. 5. The same as in Figure 1 but from two forks of Horse Creek.

curred during the selected period. A total of 10 sediment records, including those from the Alsea Watershed study, satisfied the criteria (Table 1).

Of the 10 records, the two from watersheds WS1 and WS3 in the H. J. Andrews Experimental Forest, Oregon, describe recently disturbed systems. WS1 was completely clear-cut between 1962 and 1966. WS3 was 25% patch-cut in 1962–1963, but a large storm in water year 1965 produced numerous landslides in the watershed, and the resulting debris torrents scoured nearly all of the stream channel [*Fredriksen,* 1970]. The data used here for WS3 span the 11 water years immediately following this major event. The other eight records are from unlogged watersheds.

Because WS1 and WS3 were logged, there was a strong possibility that, following an initial increase after disturbance, their sediment yields decreased over time. Two tests were applied to detect nonstationarity. Following the procedure used in paired watershed studies, the annual yields were first normalized with respect to yield data from the undisturbed control watershed, WS2 [*Fredriksen,* 1970; *Beschta,* 1978]. Let $Y_A{}^D$ equal the yields from the disturbed watersheds (WS1 and WS3), and let $Y_A{}^U$ equal the yields from the companion undisturbed watershed (WS2). Then the tests were applied to $Y_A{}^D/Y_A{}^U$ and also $(Y_A{}^D - Y_A{}^U)$ for both WS1 and WS3.

A run test [*Bendat and Piersol,* 1971] could not reject the hypothesis of randomness in time ($p > 0.05$ for all four cases).

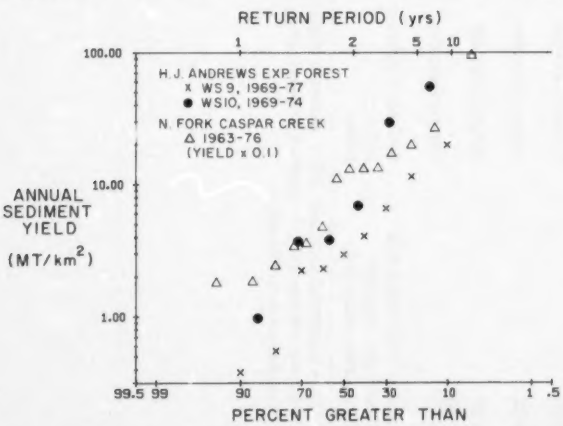

Fig. 4. The same as in Figure 1 but from sites in the H. J. Andrews Experimental Forest and the North Fork of Caspar Creek.

In addition, an attempt was made to correlate the normalized annual yields directly with time. In none of the four cases were correlation coefficients significantly different from zero ($p > 0.10$). Although the tests here hampered by small sample sizes, it appears that the frequency distribution of annual yields from WS1 and WS3 can be considered time-invariant over the postdisturbance periods.

Table 1 summarizes some physical characteristics of the 10 watersheds. All of the drainages lie in mountainous terrain, but they span considerable ranges in basin area and in annual rainfall. In the Horse Creek watersheds, runoff is dominated by spring snowmelt. The Oregon Cascade streams have peak flows during October–April due to both rainfall and rapidly melting snow events. In the remaining streams, rainfall events account for nearly all of the runoff.

The annual sediment yields from Needle Branch and Flynn Creek are plotted in Figures 1 and 2. Figures 3–5 are probability plots of annual yields from the other eight streams. In all cases the annual yield plots appear reasonably linear. That is, the annual yield distributions are approximately log normal. Sample size permitting, the empirical cdf's of Figures 1–5 were tested for goodness of fit to a log normal distribution. The χ^2 statistic was calculated by assigning observed values to equiprobable categories, and the results are listed in Table 1. None of the cdf's were significantly different from a log normal distribution ($p > 0.20$ in all cases). However, except for the model-generated cdf's, the sample sizes are probably too small to make the χ^2 tests as convincing as the visual evidence.

Megahan [1975] has also performed a frequency analysis of annual sediment yields from undisturbed streams. These eight streams, in the highly erosive Idaho batholith area, range in size from 0.3 to 5.5 km², and each has between 7 and 9 years of annual yield record. Megahan used a log Pearson III frequency analysis, and the fitted curves are plotted on logarithmic, normal probability paper. Of the eight curves, five are essentially straight lines. As *Benson* [1968] points out, the log normal can be viewed as the special case of a log Pearson III with zero skew. The other three empirical distributions of log-transformed annual yields indicate that extremely high or low annual yields are slightly less probable than would be predicted by the log normal model.

Discussion

The preceding sections have shown that long-term distributions of annual sediment yields from small, mountainous wa-

tersheds are approximately log normal. The word 'approximately' is important; we have proposed no physical mechanism for the log normal property. Instead, this property appears to be a consequence of three general, empirical characteristics of sediment transport in small streams: (1) nearly all of the load is carried during brief, high-intensity runoff events, (2) frequency curves of discharge intensities have a pronounced positive skew, and (3) sediment load and discharge are related by a power function (equation (2)) with exponent equal to approximately 2 [*Wolman*, 1977].

The log normal property has interesting implications for interpretation and sampling of annual yield data. First of all, most sedimentation studies report 'mean annual sediment yield' as the single number which best summarizes sediment production from a watershed [e.g., *Fredriksen*, 1970; *Beschta*, 1978; *Rice et al.*, 1979]. In addition, the flow duration curve-rating curve method, mentioned earlier, estimates average annual yield [*U.S. Department of Agriculture*, 1975].

But if the frequency distribution of annual yields is significantly skewed, then the arithmetic mean is a poor indicator of 'average' conditions. In particular, if the annual yield distribution is approximately log normal, then the median annual yield is a more descriptive summary statistic.

Recall that Y_A is the annual yield, and let μ_Z and σ_Z be the mean and standard deviation, respectively, of $Z = \log_e Y_A$. Since Z is normally distributed, μ_Z and σ_Z are estimated from log-transformed data by the conventional formulae for the sample mean and variance. The median M of the annual yield distribution is then $M = e^{\mu_Z}$ [*Aitchison and Brown*, 1957]. Compared with μ_Z, the median has the advantage of having the same units (weight of sediment/area year) as the original data.

A second outcome of the log normal interpretation is that analytical procedures based on normal statistics can sometimes be used in testing the effects of watershed disturbance on annual sediment production. To test the impacts of road construction and logging in the Pacific Northwest, researchers have often used experimental designs which compared the disturbed watershed to a nearby control (undisturbed) drainage [*Fredriksen*, 1970; *Brown and Krygier*, 1971; *Harr and McCorison*, 1979; *Rice et al.*, 1979]. The strategy successfully factors out most of the high year-to-year variability seen in runoff and sediment production. However, if this variability can be statistically described, it may be possible to make direct, predisturbance versus postdisturbance comparisons of key hydrologic variables. Such comparisons are necessary when a control watershed is not available.

Finally, the log normal property allows one to estimate the sampling time needed to estimate accurately the median yield. Assuming normality, *Snedecor and Cochran* [1967] give the approximate sample size n required to determine the mean within the limits $\mu \pm L$, with 95% confidence. The formula is $n = 4\sigma^2/L^2$, where σ^2 is the population variance. Table 1 lists estimates of σ_Z, and we take $L = \log_e 2$. The calculated values of n range from 3 years (Horse Creek) to 19 years (WS10), with the majority of the watersheds requiring more than 8 years ($\hat{\sigma}_Z \geq 1.0$). The sampling time estimates may be more easily interpreted in terms of the untransformed yields. Suppose the median annual yield is obtained from the formula $M = e^{\mu_Z}$. Then for most of the watersheds in Table 1, more than 8 years of sample data are needed to determine M, with 95% confidence, to within the interval $[M/2, 2M]$.

These results help to quantify what we already know, namely, that sediment yields from small watersheds are highly variable and that long-term monitoring is necessary to characterize annual sediment production from observations alone. But long-term studies are feasible for relatively few watersheds. There is clearly a need for models, both stochastic and deterministic, which can summarize and augment the information obtained from a 1- or 2-year sediment sampling program.

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